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ARTICLE

A Comparison of Salt Marsh Construction Costs with the Value of Exported Shrimp Production

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Abstract Penaeid shrimp support valuable fisheries in the northern Gulf of Mexico, and shrimp productivity has been linked to coastal salt marshes. Continuing wetland loss in Galveston Bay, Texas (USA) has led to the development of various salt marsh restoration projects. These constructed wetlands often attempt to mimic natural marsh landscape characteristics within the region and incorporate marsh edge, because marsh edge appears important for fishery production. We estimated the value of shrimp production from nine of these constructed wetlands for comparison with project construction costs that ranged between \$9,555 and \$45,311 ha^{-1} (2007 U.S.) Overall annual shrimp production attributable to the constructed wetlands ranged from 228 to 318 kg ha^{-1}. After adjusting for natural mortality and production expected from open water replaced by marsh, the constructed marshes contributed an enhanced annual shrimp production between 90 and 146 kg ha^{-1}. The annual value of this shrimp production from the nine wetlands ranged from \$425 to \$690 ha^{-1}, based on the ex-vessel price of shrimp harvested in Galveston Bay. In relation to construction costs, shrimp production was higher for marsh terracing projects and small marsh islands built with nearby sediment than for marsh islands built with dredged sand.

Keywords Economic value · Fishery · Penaeid shrimp · Secondary production · Wetlands

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Introduction

Brown shrimp (*Farfantepenaeus aztecus*) and white shrimp (*Litopenaeus setiferus*) support two of the most valuable fisheries in the United States, and Gulf of Mexico (GoM) landings in 2007 were valued at \$344 million US (NMFS 2009). Productivity of these shrimp species in the GoM has been linked to coastal wetlands used as nursery habitats (Turner 1977; Zimmerman et al. 2000). The salt marshes in Galveston Bay, Texas (USA) are characterized by large populations of juvenile shrimp, and shrimp production has been related to the amount of marsh edge (Minello and Rozas 2002; Minello et al. 2008). In response to wetland loss in the bay caused by relative sea level rise and shoreline erosion (White et al. 1993, 2004; Ravens et al. 2009), a variety of salt marsh restoration techniques have been developed and implemented. Production of shrimp from these created wetlands is one indicator of their fishery and ecosystem value.

Objectives of marsh restoration often include shoreline protection, aesthetics, long-term viability, nutrient recycling, habitat for marsh organisms, and fishery production (National Research Council 1992; Zedler 1996; Craft et al. 2009). When fishery production is a primary objective, construction designs often attempt to mimic natural marsh landscape characteristics and maximize marsh edge (Rozas et al. 2005). Such projects generally appear successful in

creating valuable nursery habitat for shrimp and other nekton (Rozas et al. 2007), although questions regarding ecosystem value persist (Bush Thom et al. 2004; Feagin and Wu 2006; La Peyre et al. 2007). Local site conditions often control the suite of viable restoration techniques, but in situations where a variety of construction approaches are possible, information on construction costs versus fishery benefits may be useful in deciding how to build marshes.

Our objective was to estimate shrimp production from nine constructed salt marshes in Galveston Bay and compare the value of this fishery production with the cost of constructing the marshes. In an earlier analysis, Rozas et al. (2005) examined five of these marshes and compared construction costs with standing crops of shrimp and other fishery species. This current analysis includes four more recently constructed marshes, provides for inflation in calculating construction costs, and estimates annual shrimp production (as opposed to standing crop) using a modeling approach developed for natural marshes that incorporates growth and natural mortality (Minello et al. 2008). In addition, we have estimated the ex-vessel value of shrimp production exported from these created marshes for comparison with the cost of marsh restoration.

Methods

The nine constructed marshes were located in the lower Galveston Bay system of Texas (Fig. 1) and could be placed into three categories depending upon construction techniques. Five of the marshes were classified as terraces or small marsh islands (Table 1) and were constructed in shallow water with a backhoe or small bulldozer. Elevated ridges or islands were built using sediments from the adjacent bay bottom or from a nearby stockpile (Mason Marsh). Three of the remaining marshes consisted of emergent mounds or islands built with a small hydraulic dredge that pumped sandy substrate from a borrow area in deeper water of the bay. The remaining project (I-45 West) also involved construction of marsh islands, but this work was done under “dry” conditions in an area of degraded wetlands that had been converted into a dredge disposal site. Heavy earth moving equipment was used to create ponds and islands from stockpiled sediment. Upon completion, containment levees were breached to flood the project area.

We assessed the patterns of vegetated land and water for each marsh through a Geographic Information System (GIS) analysis based on digital color orthophotography at 1/4800 scale taken in 2006 by Kucera International Inc. for the Houston-Galveston Area Council (available at http://www.h-gac.com/rds/). GIS models of each marsh system were developed by onscreen digitization of the edge of the marsh vegetation using ArcGIS 9.2, the Spatial Analyst extension, and the Editor Tool Bar (ESRI, Redlands, CA). There was not a lot of spectral confusion in these images, and marsh vegetation was usually distinct from nonvegetated areas. No formal ground truthing was conducted, but sites were visited and local experts consulted to ensure that no major classification errors occurred. We consider the final GIS images to be models, because several subjective decisions were needed to make equivalent comparisons among the different constructed marshes. In situations where emergent marsh areas had not been completely vegetated, we assumed that these areas would fill in with time and classified the areas as marsh. In addition, some of the constructed wetlands were located near natural marsh or breakwaters, and we used the GIS software to substitute shallow water for such areas adjacent to constructed marsh. This approach allowed us to compare projects as if they were all constructed in open shallow water and prevented adjacent habitats from affecting the modeled estimates of shrimp production. Without this substitution, for example, the natural marsh adjacent to the Delehide Cove project would have been incorporated into the buffer surrounding this constructed marsh and likely increased our shrimp production estimates for the project.

Defining a project area, and therefore the size of a project, is important in obtaining funding and assessing project success and performance. The projects we analyzed were designed to incorporate marsh edge, based partly on studies showing elevated nekton densities both in the vegetation and open water adjacent to this edge (Minello et al. 1994; 2008). Therefore, proposed project areas should include both emergent vegetation and shallow water. Because the outer project boundaries affect area and construction cost calculations, we standardized the designation of these boundaries and defined the project area using a 25-m buffer around marsh vegetation (Fig. 2). Small amounts of water greater than 25 m from marsh that were within these outer boundaries (less than 2.4% of any project area) were included in the project area. We also provided calculations of construction costs in relation to strictly the area of emergent marsh.

Population size and annual production for brown shrimp and white shrimp were estimated following the methods described in Minello et al. (2008). Bands of vegetation and water at different distances from the marsh edge were constructed with the GIS. Our modeling approach then assigns shrimp densities to these bands based on observed density patterns across the natural marsh surface in Galveston Bay. These densities peak in the vegetated marsh edge at 13.4 brown shrimp m^{-2} and 8.9 white shrimp m^{-2} and decline both into the vegetation and out into open water. Shrimp population estimates for a project area are derived from these density patterns combined with infor-

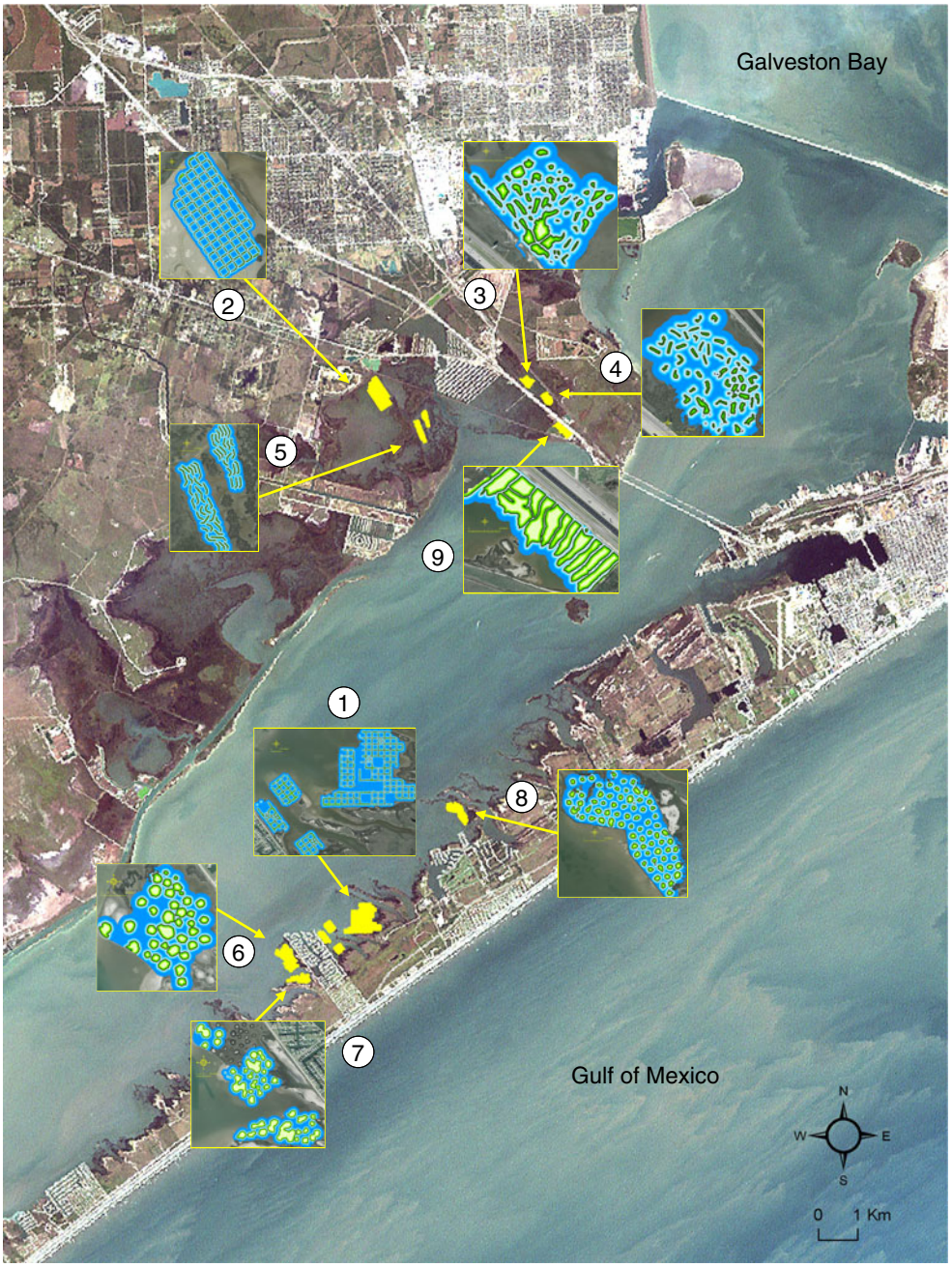

Fig. 1 Locations of nine constructed wetlands in lower Galveston Bay, Texas (29.57° N 94.93° W). The site numbers identify projects in Table 1. Inlaid images show land (green) and water (blue) patterns. The aerial image was taken in 2006

mation on the proportion of the project area at different distances from the marsh edge. Marshes that maximize the amount of marsh edge ecotone generally have the highest population values. Production is then estimated using an equilibrium yield approach that assumes stable size frequency distributions (estimated from a large database of shrimp collected in the bay) and constant daily growth rates of 1 mm total length (Minello et al. 2008). The applicability of our models to constructed wetlands is supported by the similarities in shrimp density patterns and growth rates between the GISP terrace marsh and a natural reference marsh (Rozas and Minello 2007; 2009).

This modeling approach provides estimates of total annual shrimp production from wetland habitats that include the production lost to natural mortality. Roth et al. (2008) used an individual based model to examine effects of marsh landscape configuration and tidal inundation on brown shrimp production from wetlands, and they estimated that 37.5% of total production was lost to predation. Based on these results, we estimated that 62.5% of shrimp total biomass production would be exported to the bay and be available to fishers.

We calculated the value of the additional exported shrimp production based on the average ex-vessel shrimp

Table 1 Area and estimated construction costs for nine created salt marshes in lower Galveston Bay, Texas. Project locations are shown in Fig. 1. Marsh area only includes emergent land while the project area includes water adjacent to marsh vegetation. Marsh edge is defined as the area of a 1-m wide band of vegetation along the marsh edge. Five of the marshes (1, 2, 3, 6, 9) were analyzed by Rozas et al. (2005)

Project	Year Constructed	Project Area (ha)	Marsh Area (ha)	Percent of Marsh Edge in Project Area	Total Construction Cost (2007 dollars)	Cost per Project Area (\$ ha^{-1})	Cost per Marsh Area (\$ ha^{-1})	Cost per Marsh Edge (\$ m^{-2})
Terracing and island construction								
1. GISP Terraces	1999–2000	69.2	11.3	4.1%	\$661,206	\$9,555	\$58,425	\$23
2. Pierce Marsh I	1999	31.8	5.1	4.8%	\$383,731	\$12,067	\$75,464	\$25
3. Mason Marsh	2001	7.6	1.9	4.8%	\$99,248	\$13,059	\$52,811	\$27
4. Minello Marsh	2003	7.4	1.1	4.4%	\$72,446	\$9,790	\$63,830	\$22
5. Pierce Marsh II	2005	15.8	3.0	4.7%	\$182,474	\$11,549	\$60,883	\$24
Hydraulic dredging								
6. Jumbile Cove I	2001	13.7	4.6	3.2%	\$280,343	\$20,463	\$60,989	\$64
7. Jumbile Cove II	2003	25.6	9.9	2.7%	\$312,806	\$12,219	\$31,623	\$45
8. Delehide Cove	2003	17.3	3.7	3.3%	\$469,989	\$27,167	\$125,641	\$81
Upland restructuring								
9. I-45 West	1999	10.7	5.7	4.4%	\$484,828	\$45,311	\$85,255	\$102

price obtained by fishers in Galveston Bay in 2007. We made the assumption that the additional shrimp would be caught by current fishing effort levels in the Bay and hence did not adjust the value for any additional harvesting cost. We acknowledge that the use of dockside price does not estimate the overall economic value of shrimp production, but measurements of producer and consumer surplus over time were beyond the scope of this analysis. An exhaustive

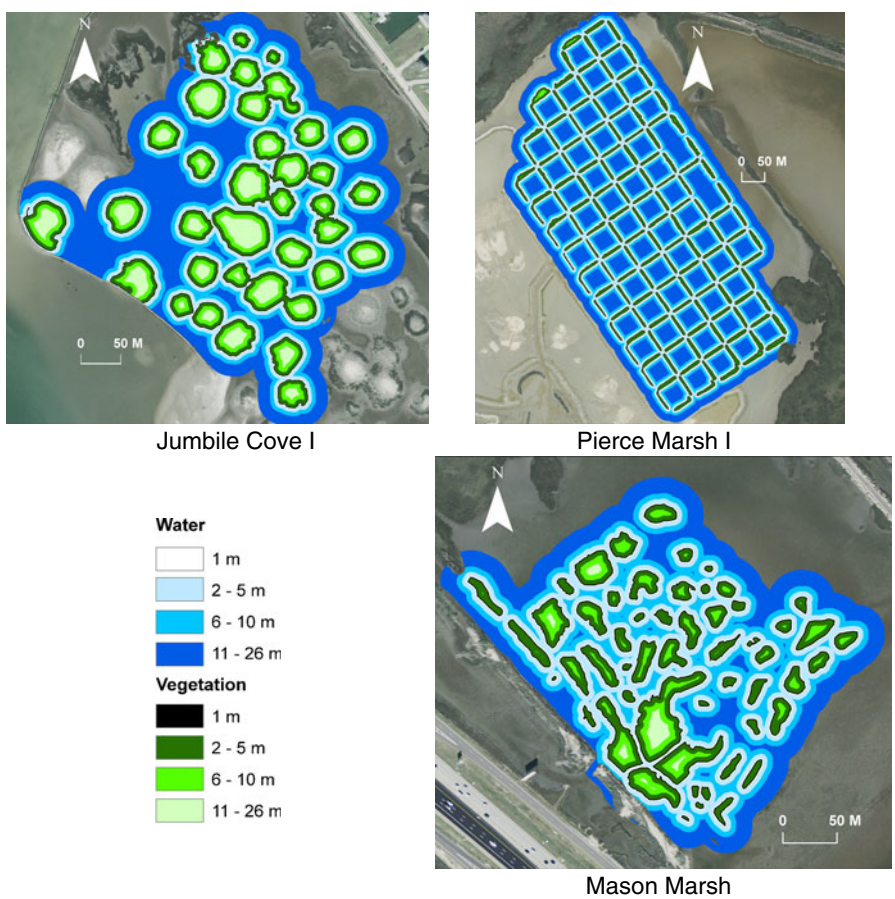

Fig. 2 Examples of land-water patterns at three constructed salt marshes in Galveston Bay. A GIS land-water analysis of the project area is overlaid on the aerial photograph taken in 2006. Color codes identify different width bands of water or vegetation in relation to the marsh edge

economic study of the net benefits of wetland restoration would require a comprehensive accounting of production changes for all commercial species and the consideration of all non-market values generated. Catch and price data were provided by the Texas Parks and Wildlife Department for whole shrimp (corrected from heads off values when appropriate) landed from West Bay, where most of the marsh restoration projects were located in the Galveston Bay system. In 2007, the catch composition included shrimp for bait (11.6% live bait and 5.5% dead bait; brown shrimp and white shrimp combined) and for human consumption (1.5% white shrimp and 81.4% brown shrimp). Of these categories, the ex-vessel price of live bait was highest at U.S. \$8.07 kg^{-1} (\$3.66 lb^{-1}), and the overall weighted-average price of the landings was \$4.72 kg^{-1}. This latter price was used to estimate the value of the exported shrimp biomass from the constructed marshes. Our assumption that shrimp produced from the constructed wetlands will be caught in the bay is another simplification. However, natural mortality of shrimp declines substantially once they reach the subadult stage (Minello et al. 1989, Baker and Minello 2010), and shrimp not caught in the bay will migrate offshore and likely be harvested by the Gulf of Mexico shrimp fleet at a larger and more valuable size (Nance et al. 1994).

We obtained construction costs from project managers, resource agencies, and local sponsors. These costs were categorized into 1) engineering design; 2) equipment mobilization and demobilization; 3) construction of wetland platforms (e.g., terraces or mounds); 4) construction of breakwaters to prevent erosion; and 5) planting of marsh vegetation. To facilitate the comparison of projects, we tried to include only items 1–3 in our estimates of construction costs. Costs of engineering design were included when available, but some projects benefited from previously developed engineering specifications. We did not include the cost of building breakwaters or wave barriers to protect the sites. The necessity for constructing such barriers is site specific and was limited to three projects (GISP Terraces, Jumbile Cove I, and Delehide Cove). Including these large costs (which could be avoided by selecting an alternate site) would unduly bias the overall estimates. We also did not include the cost of planting vegetation, because most projects employed volunteers and did not have to bear these costs. All costs were adjusted for inflation and standardized to 2007 U.S. dollars based on a Composite Cost Index developed by the U.S Army Corps of Engineers for Civil Works construction projects (USACOE 2009).

We used two approaches to compare project construction costs with the estimated value of shrimp production from a marsh. The first approach was to calculate the internal rate of return and requires an assumption about the expected lifetime of the marsh. If a marsh project is conceived of as a financial investment, then the internal rate of return is equivalent to the annual financial return an owner would receive on that investment over its lifetime in addition to the return of the capital. We made the assumption that the marshes would exist and generate the additional shrimp for 50 years beginning 2 years after construction was completed. The second approach estimates how many years it would take to recover the construction costs with continual shrimp production and does not require any assumptions about the expected lifetime of a project. This approach, however, requires an assumption about the discount rate. The discount rate is a value judgment that embodies society's preference for consumption today over consumption tomorrow. The concept is partially reflected in calculations of a financing cost, such as the interest rate on a loan used to pay for the construction costs. We calculated two measures using this approach, one with a zero discount rate and one with a 3% discount rate.

Results

The nine marshes were constructed in lower Galveston Bay between 1999 and 2005, and project areas varied from 7.4 ha (1.1 ha of emergent marsh) at Minello Marsh to 69.2 ha (11.3 ha of emergent marsh) at the GISP Terraces (Table 1). Actual construction costs varied from U.S. \$57,000 to \$477,364. After adjusting for inflation, these costs ranged from \$72,446 to \$661,206 in 2007 dollars (Table 1). When standardized for project area, construction costs ranged from \$9,555 ha^{-1} for the GISP Terraces to \$45,311 ha^{-1} for the I-45 West project. This disparity was reduced, however, when we calculated the cost in relation to the area of emergent marsh or the amount of edge habitat.

Our models projected that the total annual production of brown shrimp and white shrimp combined from the nine marshes would range from 228 kg ha^{-1} at Jumbile Cove II to 318 kg ha^{-1} at Mason Marsh. From these values we subtracted the expected production from the shallow open water replaced by the marshes (84.3 kg ha^{-1}) and an estimated 37.5% lost to natural mortality (Roth et al. 2008). The final values representing the enhanced or additional shrimp production from the constructed marshes ranged from 90 kg ha^{-1} at Jumbile Cove II to 146 kg ha^{-1} at Mason Marsh (Table 2). Mean production from the five terracing and island construction projects was 134.9 kg ha^{-1} and was significantly higher than the mean of 102.6 kg ha^{-1} for hydraulic dredging projects (t test, p=0.007).

At 2007 shrimp prices, the ex-vessel value of this additional annual shrimp production ranged from \$425 ha^{-1} at Jumbile Cove II to \$690 ha^{-1} at Mason Marsh (Table 2). The Minello Marsh and the GISP Terraces produced the

Table 2 Comparison of marsh construction costs with the value of annual production of brown shrimp and white shrimp (combined) derived from these wetlands in Galveston Bay, Texas. Shrimp production from the shallow open water replaced by marshes and that lost to natural mortality has been subtracted from overall production values. All figures have been adjusted to 2007 dollars. The Internal Rate of Return is based on a 50-year marsh life with constant shrimp production. The number of years needed to recover construction costs assumes that maximum shrimp production occurs 2 years post construction and is shown without discounting future production values and with a 3% annual discount rate.

Project	Construction Cost/ Project Area ($ ha^{-1})	Annual Shrimp Production (kg ha^{-1})	Annual Shrimp Value in 2007 ($ ha^{-1} year^{-1})	Internal Rate of Return	Years to recover cost	
					Without Discounting	3% Annual Discount Rate
Terracing and island construction						
1. GISP Terraces	$9,555	122	$575	5.3%	18.6	25
2. Pierce Marsh I	$12,067	136	$641	4.5%	20.8	30
3. Mason Marsh	$13,059	146	$690	4.5%	20.9	30
4. Minello Marsh	$9,790	126	$595	5.3%	18.4	25
5. Pierce Marsh II	$11,549	144	$682	5.1%	18.9	26
Hydraulic dredging						
6. Jumbile Cove I	$20,463	107	$505	0.8%	42.5	never
7. Jumbile Cove II	$12,219	90	$425	2.3%	30.8	75
8. Delehide Cove	$27,167	111	$522	−0.2%	54.0	never
Upland restructuring						
9. I-45 West	$45,311	139	$658	−1.2%	70.9	never

highest ratios of shrimp value in relation to construction cost, with annual rates of return of 5.3% on the cost of construction (Table 2). The I-45 West marsh was the most expensive marsh to build on a per hectare basis and had a negative internal rate of return. Because shrimp production in the models is based on the amount of marsh edge present, the cost of constructing marsh edge (Table 1) also can be used as a metric for comparing marshes. The internal rate of return was highly correlated with the cost of constructing edge (R^2=0.966).

Without discounting the value of future shrimp production, the cost of construction for all five of the terracing and island construction marshes could be generated in less than 21 years through shrimp production alone (mean 19.6 years, SE=0.55). At a 3% annual discount rate, the time to recover construction costs for these marshes ranged between 25 and 30 years (Table 2). The three marshes with the highest construction costs per hectare break even only after 42–71 years with a zero discount rate, and these marshes would never produce enough shrimp to cover construction costs if we used a 3% discount rate.

Discussion

The nine constructed marshes varied substantially in both project area (7.4–69.2 ha) and overall adjusted construction costs ($72,446 to $661, 206). In general, terraces and small island marshes constructed with nearby sediment were relatively inexpensive to build when costs were calculated in relation to the project area or in relation to the amount of marsh edge created. The annual value of additional shrimp production from constructed marshes ranged from $425 to $690 ha^{-1}, and in relation to construction costs the greatest value was derived from terrace marshes (GISP Terraces, Pierce Marsh I and II) and small islands built with a backhoe or a bulldozer (Mason Marsh, Minello Marsh). The annual rates of return for these marshes (above 4.5%) and the time needed to recover construction costs (<21 years without discounting) suggest that these restored marshes are good investments on the basis of shrimp production alone. Emergent mounds or islands built using a small hydraulic dredge (Jumbile Cove I and II, Delehide Cove) generally produced less shrimp in relation to the cost of construction. Because the shrimp production models are highly influenced by the amount of marsh edge, the cost of creating marsh edge was closely related to the economic benefits derived from shrimp production.

Objectives in marsh creation and local site conditions can affect the selection of construction methods. Compared with marsh terraces, marsh islands built with a hydraulic dredge can be more aesthetically pleasing (Fig. 2), can provide more high elevation inner marsh that may be valuable as habitat for other fauna, and can potentially have increased longevity. The choice of construction method and the associated costs also can be dictated by site conditions such as water depth, sediment type, accessibility, and wave energy. We did not include wave barriers in our estimates of

construction costs, and these costs can be substantial. For example, including the cost of wave protection for the GISP Terraces would have increased construction costs by 140%.

Our analysis was based on the additional shrimp produced from the constructed wetlands above the production expected from the shallow open water where the marshes were built. Assuming that the exported shrimp are harvested, these projections show that marsh construction can return a product of substantial economic value. These fishery benefits, therefore, are unlike many other wetland benefits that are often intangible and cannot easily be monetized. In addition to shrimp, other fishery production also should be considered in evaluating these marshes. For example, blue crab (*Callinectes sapidus)* production from these wetlands is comparable to shrimp production (Minello et al. 2008); and all crustacean production lost to natural mortality (and not included in our calculations) contributes to productivity of popular game fish such as southern flounder *Paralichthys lethostigma*, spotted seatrout *Cynoscion nebulosus*, and red drum *Sciaenops ocellatus* (Minello et al. 1989).

Our models of shrimp production were developed for natural marshes in lower Galveston Bay, but we believe that they are applicable to these constructed marshes as well. This conclusion assumes that density, growth, and mortality are similar in natural and constructed marshes of the system. Earlier studies in Texas and western Louisiana showed instances of reduced shrimp densities at the marsh edge in some created salt marshes compared with natural marshes (Minello and Zimmerman 1992; Minello and Webb 1997; Rozas and Minello 2001), but elevation of the marsh surface (reflected in tidal flooding duration) may explain some of these differences (Minello and Webb 1997; Roth et al. 2008). More recent studies that show similarities in shrimp densities and growth between the terrace marshes and a natural reference marsh support the validity of our models in representing shrimp production from the constructed wetlands (Rozas and Minello 2007, 2009; Merino et al. 2010). Causes of error in estimating shrimp production from wetlands were discussed in Minello and Rozas (2002) and Minello et al. (2008), and most of these sources of error are not expected to vary among the constructed marshes we examined. Therefore, relative comparisons of shrimp production among the constructed marshes are likely robust.

Information on the importance of edge and landscape characteristics was partly responsible for the design of the nine marshes examined in this study (Minello and Rozas 2002). Despite attempts to simulate natural landscape patterns in these constructed marshes, the amount of marsh edge was generally lower than in natural marshes (Rozas et al. 2005). Annual shrimp production (both species combined) from the nine constructed marshes (before subtracting losses to natural mortality) ranged from 228 to 318 kg ha^{-1}. Using the same models (with a 25-m buffer of water), a comparable estimate for shrimp production from natural marshes of lower Galveston Bay is 323 kg ha^{-1} (Minello et al. 2008). Thus, while some of the constructed marshes produce shrimp near the estimate for natural marshes in the bay, their mean annual production of 282 kg ha^{-1} (SE=10.2) appears lower than that from natural marshes.

Our estimates of shrimp productivity depend upon temporal characteristics of these constructed wetlands. In our calculations, we assumed that the constructed wetlands would become fully functional with respect to shrimp production after two years. This conclusion was based on the rapid development of vegetation cover and shrimp densities in marshes created on channel maintenance dredge material (Minello 2000) and on the shrimp densities measured at the GISP Terraces 2–3 years following construction (Rozas and Minello 2007). Variability in sediment sources and elevation of the marsh surface is likely to affect this estimate (Minello and Webb 1997). Future shrimp production will depend on marsh longevity, and marshes built with some construction techniques may be more enduring than others. Topographic profiles are likely important, and islands built with hydraulic dredge material, which have a relatively high center elevation, may resist subsidence and erosion more than marshes with low and flat profiles. Although we have not quantified this variability among projects, more recent aerial photography and site visits show that many of the GISP marsh terraces have eroded, while Pierce Marsh terraces are stable. This observation suggests that some differences in longevity are site specific rather than related to construction techniques. Substantial wave action at GISP (requiring wave barriers) along with differences in sediments (sand at GISP and more clay at Pierce marsh) may be responsible for differences in stability between these terrace marshes (Feagin and Wu 2006; Feagin et al. 2009). Terrace marshes can be stable, and aerial coverage of a terrace marsh in Louisiana actually increased over a 10-year period following construction (Good et al. 2005). Monitoring of wetland cover and stability of marsh platforms is needed over time to assess the durability of these constructed wetlands and the sustainability of their fishery production.

It was not our intent to assess the overall economic value of wetlands in this study or to conduct a full cost-benefit analysis. Instead, we focused on the value of shrimp production alone. The value of annual shrimp production from natural marshes in lower Galveston Bay can be estimated at \$953 ha^{-1}, using a production value of 323 kg ha^{-1}, our correction for natural mortality, and an ex-vessel value of \$4.72 kg^{-1}. Comparisons of this marsh value with others in the literature are complicated because

we have only considered production of shrimp from the wetlands; we have not adjusted the value for possible increases in harvest costs; the definition of a wetland (e.g., the amount of water included) can affect estimates; and fishery production from wetlands is expected to vary geographically (Day et al. 1973; Kneib 2003; Minello et al. 2008). A variety of approaches described by Lynne et al. (1981), Costanza et al. (1989), and Barbier et al. (1997) have been used to calculate the economic value of fishery production from wetlands, but estimating the basic fishery production values derived from a wetland remains a major obstacle in such analyses. Wetland habitats also provide other ecological services that have economic value, and Costanza et al. (1997) calculated that the annual economic value of six ecosystem services for one hectare of tidal marsh was $9,990 (1994 U.S. dollars). This figure included $466 ($652 in 2007 U.S. dollars) in food production, which may be an underestimate for Galveston Bay marshes, considering our estimate for shrimp production alone.

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